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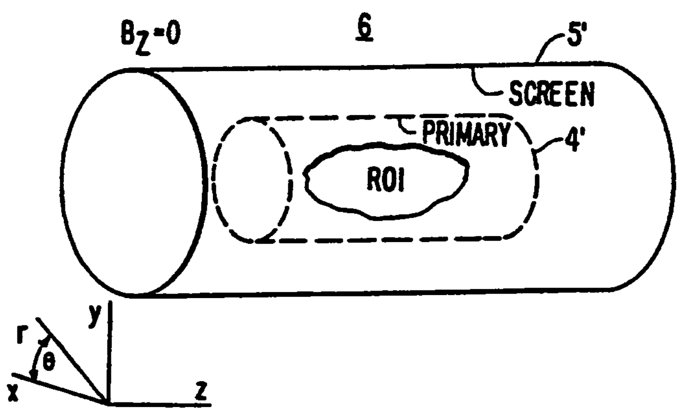

(57) Abstract

A primary gradient coil (4′) and a screen coil (5′) with the primary coil (4′) are constructed to create a substantially null field adjacent to the gradient coil (4′). This coil (3) related to active electromagnetic field screen coils of restricted length and a method of optimizing the magnetic fields created by such coils over one proximate volume while maintaining a null field over a second proximate volume. A method is disclosed for generating the coils (4′, 5′) by considering the screen coil to be of infinite length, deriving a Fourier transform of the axial and other components of the field in which the transform is the sum of the permissible harmonic modes on the coil surface in which a coefficient C_n is derived representing the nth harmonic. A perfect screen coil is created and the number of terms C_n selected using least squares optimization until there is no longer a significant change in the resulting field. Examples are given in for creating unscreened, screened, linear, axial and transverse gradient coils.

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SCREENED ELECTROMAGNETIC COIL OF RESTRICTED LENGTH HAVING OPTIMIZED FIELD AND METHOD

Field of the Invention

This invention relates to active electromagnetic field screen coils for use with coils of restricted length and a method of optimizing the magnetic fields created by such coils over one proximate volume while maintaining a null field over a second proximate volume.

Background of the Invention

Electromagnetic coil design is of great importance in many fields of physics and engineering. This is particularly true at the present time in Nuclear Magnetic Resonance (NMR) imaging and spectroscopy where the requirement for precise spatial variation of a variety of magnetic fields is paramount. The most common arrangement of electromagnetic coil structures for use in NMR is illustrated in Figure 1 in which system 1 comprises: a control 2 for operating the system, a main coil 3, usually superconducting, which provides a large, uniform, substantially homogeneous magnetic field over a region of interest (ROI) in the center of the structure and one axial and two transverse linear gradient field coils 4 (only one being shown for purposes of illustration) that are intended to provide three orthogonal gradient fields that vary linearly over the ROI. The gradient coils shown include active screen coils 5.

Screened or shielded gradient coils, and occasionally screened main field coils, have become preferred structures for NMR systems. Active screened coils are described in an article entitled Active Magnetic Screening of Gradient Coils in NMR Imaging by Mansfield et al. J. of Magnetic Resonance 66, p. 573-576 (1986) which discloses a method of systematically screening static or time-dependent stray fields. In this method extraneous magnetic fields outside the active volume of the field gradient coil systems are nulled while gradient fields of a desired type are intended to be generated in the ROI. Subsequent developments have resulted in integrated coil systems wherein primary gradient coils and screen coils cooperate with one another to produce the gradient magnetic fields in the ROI

adjacent to the primary coil structure while creating the external null field. Screened coils are such that they provide for a field of a specific type, e.g., a uniform field, a linear field and so on, within the ROI adjacent to the primary coil structure while simultaneously providing a substantially zero field adjacent to the screen coil structure.

In Figure 2, a cylindrical embodiment of the invention, the screen coil 5' and the primary coil 4' are intended to create a given desired type of field in the ROI while providing a null field $Bz=O$ in the region external relative to screen coil 5'. Screened coils are used to eliminate time dependent eddy currents in proximal conducting structures, and hence the resultant time dependent perturbations of the magnetic field in the ROI. It is known that the inductance of screened coils is identical to that of unscreened coils providing the same primary field, since, by definition for screened coils, all flux lines return within the screen such that there is no net flux anywhere. Further, the resistance of the screen coil is also independent of the numbers of arcs (turns) that comprise it. This property results from the fact that the more turns that are present on the screen portion of the structure the proportionally greater amount of current that must be tapped off into a parallel circuit. The reduction in current in the screen is in direct proportion to the increase in the number of turns, e.g., double the turns and the current reduces to half and the voltage drop, and thus the resistance, remains constant.

Screening also provides a means of greatly reducing the extent of the stray external field from the main coil structure which otherwise has adverse effects on all electronic devices within the local region. Consequently, it is desirable to eliminate, or at least greatly reduce, this external field. The alternative, using passive screening, requires the use of great masses of ferromagnetic material.

The significant prior art methods of approaching the general problem of electromagnetic coil design are somewhat arbitrary in their choice of a starting point for the calculation of the surface current distributions of the coils of interest. As a result the computations tend to be cumbersome, relatively slow and the resulting coils do not generate optimal fields.

The general problem of electromagnetic coil design is one of solving the Biot-Savart equation:

$$B(r) = \mu/\pi \int \frac{J(r)\ (r-r')}{|\, r-r' \,|\ 3}\ \tau\ ' \tag{1}$$

where B (the quantities in bold are vector quantities having three orthogonal spatial components) is the resultant magnetic field at the point $\underline{r}$ due to the current density distribution $\underline{J}(\underline{r}')$ flowing at all points $\underline{r}'$ within the region of interest and μ is the magnetic permeability of the medium.

Solving the Biot-Savart equation to obtain the magnetic field for a given current distribution, in all but a few very simple cases, has until recently, relied upon numerical integration methods. Solving the reverse problem, that of determining a particular current distribution to produce a desired magnetic field, is more difficult. Frequently, and particularly in the design of electromagnets for NMR, fields are generated by coils wound upon a cylindrical former. Until recently, solutions for such coils were obtained by expanding the magnetic field in terms of spherical harmonics and optimizing the first few non-zero terms at the origin. This method has been in use for over a century and results in the standard Helmholtz and Maxwell coils for uniform and linear axial gradient coil designs, respectively. This system generates designs which are essentially a series of line current elements at particular spatial locations.

According to Ampere's law, any theoretical achievable magnetic field can be generated in a region by a current distribution on a surface enclosing that region. For cylindrical coils, this involves surfaces which are either of infinite length or are closed. For practical reasons, in NMR where access to within the coil is essential, the cylinders must be relatively short and open ended. As a result, the practically achievable magnetic fields, while better than those derived by spherical harmonic expansion, are not perfect, and exhibit distortion from the desired field parameters. Therefore, some form of optimization is necessary generally based on assumption and compromises which still result in undesired

distortion of the resultant screen-primary coil generated field or compromising the null value of the external field, i.e., generating a significant stray field in the null region.

Exact solutions of the Biot-Savart equation, equation 1, which take into consideration its convoluted nature were initially derived to solve the problem of eddy current formation in structures external to gradient coils in NMR systems. These solutions have been subsequently applied to the problem of gradient coil design by Turner in 1986 in an article entitled A Target Field Approach to Optimal Coil Design, J. Phys. D:Appl. Phys. 19 (1986) L147-L151 and integrated shielded gradient coil design in an article by Mansfield et al. entitled Multishield Active Magnetic Screening of Coil Structures in NMR, J. Mag. Resonance 72, 211-223 (1987). In these latter two cases a suitable (convergent at infinity) "target" field is chosen for the primary gradient field. The choice of such a field is completely arbitrary and does not consider the invariably finite length of the primary coil surface. This results in distortion in the resultant generated field.

In an article by Turner et al. Passive Screening of Switched Magnetic Field Gradients, J. Phys. E. Sci. Instrum. 191 (1986) p. 876-879, a thick cylinder conductor is disclosed for passive screening of magnetic field gradients. However, currents induced in the sleeves decay with uncontrolled relaxation times interfering with the NMR imaging. This is because the decaying current produces image fields superimposed on the desired gradient field introducing artifacts which can ruin the image.

An article by Mansfield et al. entitled Active Magnetic Screening of Coils for Static and Time-dependent Magnetic Field Generation in NMR Imaging J. Phys. E: Sci. Instrum. 19 (1986) p. 540-545 discloses a set of current carrying conductors or a discrete wire array to simulate the induced surface currents which occur in high conductivity thick metal screens when placed around coils producing time-dependent fields or field gradients. Strong external fields are made arbitrarily low making it feasible to generate large rapidly switched gradients within and in close proximity to a superconducting magnet which is especially useful in NMR imaging. The active screen may comprise a set of conductors or a mesh of equally spaced wires in which a current pattern is externally generated to

mimic an induced surface current distribution. An alternative arrangement is one in which the screen wires carry the same current but the wire spacing is unequal. It is disclosed that the field outside the active screen is substantially nulled. However, the problem of obtaining an optimum field in the region of interest is not addressed. A disclosure corresponding to these articles appears in British Patent 2,180,943. This patent discloses the active screen as a complete reflector of the magnetic field produced by a primary coil, the screen being shaped to provide an aperture for access to a volume enclosed by the screen.

European Patent 0231879 is an alternative to the above solutions and discloses optimization of a screened coil by adding terms from a second cylindrical surface. However, the length of the screen coil is a severe constraint. The use of the total available coil length is almost always unsuitable for designing the screen parameters. This is because the requisite number of harmonic wavelengths are not necessarily alequot to this length. As a result, the fields generated by coils of this design exhibit distortion in the presence of the desired null field. A further problem with this approach is that it compromises the null field. Therefore, to eliminate the distortion in the generated field, the null field value is compromised to a non-null value, which in effect can eventually have deleterious affects on the generated field in the ROI.

Summary of the Invention

A screen coil and method according to the present invention optimizes the generated field to a given desired condition to provide minimal distortion while simultaneously providing a null field outside a region of interest in an open coil of restricted length. In accordance with the present invention, an electromagnetic coil construction for creating a magnetic field of a given type comprises a screening electromagnetic coil and an open primary electromagnetic coil of restricted length. The coils are constructed such that the current distributions in the coils are determined by least squares optimization of the current amplitudes of n harmonics of the two dimensional Fourier transform of the Biot-Savart relation to create a substantially null magnetic field in one volumetric region adjacent to the screening coil and the field of the given type is created in a second volumetric region

adjacent to the primary coil wherein the field of a given type exhibits minimal distortion.

In accordance with one embodiment the coils are constructed on two cylindrical surfaces, the inner of which is the primary coil of pre-assigned length and the outer of which is a screen coil of length 1 such that 1 encompasses the significant portion g of the total current of that coil, and the current distribution which the coil structure approximates are such that they provide simultaneously a null magnetic field external to the screen surface and a magnetic field optimized on a least square basis within a given region of interest within the primary coil to provide a field of a given form.

Brief Description of the Drawings:

Figure 1 is a diagrammatic representation of a prior art electromagnetic coil structure in an NMR system;

Figure 2 illustrates in diagrammatic form a generalized prior art screened coil arrangement for providing a field in one region of a given type and for providing a substantially zero external field;

Figure 3 illustrates an unscreened magnetic field coil current distribution in which the amplitude is constant in the azimuth direction normal to the drawing sheet on the surface of a cylinder optimized in accordance with the present invention to provide a uniform field over a cylindrical region of interest;

Figure 4 illustrates practical means of achieving the current distribution of Figure 3 wherein the lines represent a series connected structure of conductors the spacings of which are given by equally spaced contours on the integral of the current distribution of Figure 3;

Figure 5 is a sectional elevation view of an embodiment of a coil construction for generating a large uniform field in which depth is proportional to current distribution; note depths have been exaggerated in comparison with the radius for purposes of illustration;

Figure 6a and 6b illustrate coupling of coil sections between successive turns of axial and transverse coil structures, respectively;

Figure 7a and 7b illustrate current distributions for respective primary and screen coil surfaces to provide a uniform magnetic field within a region of interest and a null external field;

Figures 8a and 8b illustrate respective equally spaced contours as the integrals in the axial direction of the current distribution curves of the primary and screen surfaces depicted in Figures 7a and 7b;

Figures 9a and 9b illustrate linear axial gradient magnetic field coil current distributions restricted to primary and screen cylindrical surfaces;

Figures 10a and 10b illustrate a series of equally spaced contours of the integrals of the current distribution curves of the primary and screen surfaces depicted in Figures 9a and 9b, respectively;

Figure 11a shows the substantially undistorted linear field variation Bz over a region of interest for the screened axial gradient coil current distributions shown in Figures 9a and 9b;

Figure 11b shows the distorted linear magnetic gradient field provided by a prior art Maxwell coil of equal radius to the primary coil;

Figures 12a and 12b respectively show screened linear transverse gradient magnetic field coil current distributions on primary and screen cylindrical surfaces;

Figure 13 shows iso-contours of the screened transverse gradient coil primary current distribution on a cylinder with the cylinder unrolled in the azimuth direction showing all four quadrants in accordance with an embodiment of the present invention; and

Figure 14 is an unrolled flat view of a quadrant of a screen coil current distribution in accordance with an embodiment of the present invention.

Description of the Preferred Embodiments

In Figure 1, NMR system 1 includes a control 2 whose construction is well known and will not be further described in detail herein. The control includes the appropriate power sources including rf for energizing the coils of the system. System 1 includes a main outer coil 3 commonly used in NMR imaging systems to create a relatively large static magnet field in a region of interest (ROI), e.g., the region for receiving a patient to be examined by the NMR images. The outer coil 3 is the main coil generating the static B field for the system. Primary gradient coil 4 represent a plurality of gradient coils which generate the axial and transverse gradient fields for imaging purposes in a known way in NMR systems. The screen gradient coils are the active screening coils used to cancel the fields created by the gradient coils 4 in order to screen the surrounding metal structure.

The outer coil 3 usually is superconducting and occasionally screened (not shown). This coil provides a large, uniform substantially homogeneous magnetic field over the ROI at the center of the structure. Within this magnet resides one axial and two transverse linear gradient coils represented by coils 4. Coils 4 are intended to provide three orthogonal gradient magnetic fields that vary linearly over the ROI.

Screen electromagnetic coils 5 cooperate with the gradient coils 4 to generate a magnetic field of a specific type, e.g., uniform, linear, within the ROI while simultaneously providing a substantially zero (null) field in an external region 6, Figure 2. The screen and primary coils obtain these characteristics by having requisite current distribution flowing on their primary coil and screen coil surfaces shown here in one preferred embodiment as inner and outer circular cylindrical surfaces.

The term "distortion" herein means a field that is different than that which is intended. For example, Figure 11a illustrates a substantially linear gradient field and Figure 11b illustrates a significantly distorted field, i.e. the field is non-linear. Additionally, the open

nature of the coil of interest exhibits leakage flux which is a more difficult problem to resolve than a closed coil.

European patent 87101198.7 proposes a form of least squares optimization of a screened coil involving adding terms from a second cylindrical surface. However, the choice of length screen is arbitrary. The use of the total available length is almost always unsuitable as the requisite harmonic wavelengths for adequate screening are not necessarily multiples of this length. The prior methodology requires an assumption of a given screen coil length prior to performing the coil design calculations. Necessarily, this assumption is invariably incorrect. According to the present invention, it is recognized that for purposes of calculation, the screen can be assumed to be of infinite length. As a result, a perfect screen coil can be created, i.e., one that with the primary coil creates a respectfully null field in a first adjacent region and a substantially distortion free field of a given type in a second adjacent region. The current in the screen coil will diminish rapidly beyond the axial limits of the primary coil and its length can be determined retrospectively to impact insignificantly on the derived magnetic fields. As a result, no constraints are placed upon the screen coil design and the solution is readily obtained in which a more perfect screen produces a substantially zero external field as compared to prior art systems.

The Biot-Savart equation <u>states that the magnetic field B is given by the convolution of the current density distribution J,</u> with the inverse square of the distance $r/|\underline{r}|^3$. Therefore, the equation can be greatly simplified by Fourier transforming to a <u>simple</u> product in the Fourier Kernal space:

$$B(s) = \mu\, J(s) \wedge \frac{\underline{s}}{|s|^2} \qquad (2)$$

where B(s) is the Fourier transform of the field B(r) and J(s) is the Fourier transform of the current distribution J(r), both at the point s which is the general point of the Fourier Kernal space of that space for which r is the general point vector.

Utilizing this property permits the development of electromagnetic coils with improved gradient linearity and extent relative to the coil structure and the development of screened gradient coils. The analytic design of coils utilizing this property has relied on the choice

of a suitable function for the field with a somewhat arbitrary axial variation, which will satisfy the condition that the resultant current distribution diminishes to zero at infinity. Although the choice of a suitable function is simple it is also arbitrary, and consequently the resultant field is less than optimal.

In NMR, the main field magnets are mostly cylindrical in form, consequently, the following analysis will be presented for cylindrical coils, though much of the analysis is equally applicable to other geometries as explained below.

<u>The Elementary Primary Current Hoop</u>

Of particular importance in the solution of the Biot-Savart equation for coils wound on a cylindrical surface is the field from a hypothetical elemental current hoop of unit current amplitude which varies azimuthally as cos (m0); i.e. the permissible azimuthal harmonic modes. For simplicity, the following is confined to the determination of the axial component of the field, which will be defined simply as B, and the corresponding azimuthal current J. The other components of the current distribution, and consequently the field magnetic components, can be immediately derived from the continuity equation Div. J=O. Taking the two Dimensional Fourier Transform (2DFT) of this gives:

$$B_h(r, m, k) = \mu \begin{cases} k\ a\ I'_m(ka)\ K_m(kr) & r > a \\ \mu\ a\ I_m(kr)\ K'_m(ka) & r < a \end{cases} \qquad (3)$$

where B_h is the axial component of the Fourier transform in the azimuthal and axial directions of the magnetic field at radius r (not to be confused with vector position r), k is the kernal space dimension corresponding to the axial dimension z, a is the radius of the hoop, and I_m and K_m are the modified Bessel functions and I'_m and K'_m are their derivatives.

It is apparent from the foregoing that all solutions on a cylinder are simply convolutions of the elemental current hoop with a purely axial distribution function. For an open cylinder of restricted length L this current distribution can be expressed as the sum of the permissible harmonic modes, n, on the surface i.e.

$$J_0 (a, z) = \Sigma_n C_n H(z) \cos (2\pi nz/L + \phi) \quad (4)$$

where C_n is the current amplitude of the nth harmonic and H(z) is the unit step function given by

$$H(z) = \begin{cases} 1 & |z| \leq L/2 \\ 0 & |z| > L/2 \end{cases} \quad (5)$$

Fourier transformation of equation 4 in the z direction yields

$$J_0(a,k) = \pi L \Sigma_n C_n [e^{i\phi} \mathrm{sinc}(KL/2 - n\pi) + e^{-i\phi} \mathrm{sinc}(KL/2 + n\pi)] \quad (6)$$

The Fourier transform of the resultant axial field in the azimuthal and axial directions is given by:

$$B(r, m, k) = J_0 (a, k) . B_h (r, m, k) \quad (7)$$

Optimization of the coil design is then conveniently solved by least squares minimization of the first few terms (C_n) over the Region of Interest (ROI) in real, as against Kernal, space. The choice of the number of terms is dependent upon the geometries of the coil structure and the ROI; this can be addressed by solving with increasing numbers of terms until the cross term coefficient matrix becomes singular to, for example, one part per million, at which point no further significant improvement can be had.

<u>Screened Elemental Current Hoop</u>

The resultant Fourier transform in the azimuthal and axial directions for the internal field of an implicitly screened hoop is given by:

$$B_s(r, m, k) = \mu_0 k a I_m (kr) [K'_m (ka) - K'_m (kb) I'_m (ka)/I'_m (kb)] \quad (8)$$

where b is the radius of the infinite screen. The external field is, by definition zero.

The permissible harmonics of the primary surface of radius a, $\cos(2\pi nz/L)$, which results in the axial component of the internal field for convenient two Dimensional Fourier Transform (2DFT) of which, B, is obtained by substituting B_s for B_h in equation 7, i.e.

$$B(r, m, k) = J_8 (a, k) . B_s (r, m, k) \quad (9)$$

Optimization of the coil design is then conveniently solved as before for the unscreen case on a least squares basis for the harmonic current amplitudes C_n, without the addition of any new terms. Practically, the length of the screen must be finite, but as the current distribution will fall off rapidly beyond the length of the primary coil, the screen length

can be limited to the length at which the current distribution amplitude becomes negligible. In this way no a priori limitation has been imposed upon the screen that would impair, or even inhibit a solution for the coefficients. Nor will this current method comprise the screening and the field over the ROI.

A significant reduction in the number of coefficients can be achieved by incorporating an unconvoluted term in the series, i.e. adding a component representing the field from the current distribution for a flat surface. Examples are the field from a constant current distribution for when a uniform field is required, and a current distribution that varies linearly when a linear axial gradient is required.

The following is employed to determine the current distributions for either unscreened or screened coils structures.

a) Set the values for the physical constants, specifying the positions of the primary surface, and screen surface if required, the extent of the primary coil, and the ROI. The ROI is specified as a lattice of points over which the optimization is to be performed. For example, a screened cylindrical coil structure is specified by the screens radius b, the primary's radius a, and the primary's length L. A convenient ROI is a cylindrical volume. Symmetry considerations and perfect azimuthal variation permit such a cylindrical volume to be specified by p radii and q axial positions from the origin out; provided $p.q >$ the number of unknowns C_n.

b) Determine the magnetic field from unit current amplitude of each of the appropriate harmonics; given by the inverse Fourier transform of the individual terms of the magnetic field given in equation 7, suitably modified for screened systems. For example if a transaxial gradient is required on a cylinder only the cos(0) azimuthal variation is required and only even longitudinal terms $\cos(2\pi nz/L)$, with $n>0$, need be considered for reasons of current continuity [return path].

c) The least squares optimization is then performed with increasing number of coefficients until no significant improvement in the field in the ROI can be obtained. For the cylindrical example 2, 3, 4 etc. terms are incorporated into the coefficient matrix until it becomes non-singular to 1 part per million (ppm), at which point no further significant improvement is to be had.

d) The significant coefficients are then used to determine the total current distribution, as given by equation 4.

e) Equipotential contours are then determined in the axial and azimuthal directions. These contours are then utilized as the basis for practical manufacture of the coil structure.

The following examples constitute the three primary fields required for the performance of NMR:

1. Uniform magnetic field
   a. Unscreened,
   b. Screened.
2. Linear axial gradient field
3. Linear transverse gradient field.

The method of the present invention is immediately applicable to similar coil geometries and all ROI's geometries. Further, the method can be readily generalized to other open geometries, for example flat surfaces.

In all of the following examples, a cylindrical ROI of diameter 55 cms radius and 40 cms length was used and least squares optimization was performed over six evenly spaced radii within it.

The choices of a cylindrical ROI and all dimensions is arbitrary.

Unscreened Uniform Magnetic Field Coil

For the purposes of this example a cylindrical coil structure of 140 cms diameter restricted to a length of 200 cms is assumed.

Least squares optimization over the ROI was achieved in the manner described above with the first three harmonic terms CO, C1, and C2. Figure 3 shows the unscreened magnetic field coil current distribution (Mega Amps per Meter per Tesla versus cms) on the surface of a cylinder of diameter 140 cms and length 200 cms, optimized to provide a uniform field on a cylindrical ROI of diameter 55 cms and length 40 cms. The figure shows the current distribution that will provide such a uniform magnetic field; the amplitude of this current distribution being constant in the azimuthal direction. This distribution can be achieved by the suitable placement of conductors by a method as described in the literature. The two most common embodiments of which are the use of either conductors of uniform cross section or equally spaced conductors of varying width in the axial direction, both wound azimuthally and in series. In both cases the thickness of the conductors is assumed to be small compared to the diameter of the coil.

One means of practically achieving the uniform field is to place series wound conductors of uniform thickness along the lines indicated on the diagram, Figure 4. A second means of achieving the field is to place conductors of thickness corresponding to the spacing between lines, again connected in series; in which case the lines become the spacing between each 'loop' of the coil. Figure 4 shows a side view of the coil arrangement with 40 or 41 turns for the conductors of uniform and none uniform thickness respectively; the two extra turns in the latter case are formed by the ends of the structure which is shown here open. The front view of the structure is circular. In a practical embodiment the number of turns for the main field would be several orders of magnitude more than those depicted, and the use of uniform wires wound in such a way as to form a depth corresponding to the current distribution, Figure 5, with a compensation, not shown, for the depth, would be a convenient means of achieving it.

The contribution from connecting sections between successive turns can be made negligible by placing return paths adjacent to incoming lines, Figures 6a and 6b.

Screened Uniform Magnetic Field Coils

For the purpose of this example a cylindrical coil structure of 140 cms diameter restricted to a length of 200 cms is assumed for the primary, and a cylindrical coil structure of 200 cms diameter for the screen.

Least squares optimization over the ROI is achieved with the first three harmonic terms; as expected. Figures 7a and 7b show the current distribution for the primary, 7a, and screen, 7b, that will simultaneous provide such a uniform magnetic field with the ROI and zero field external to the screen ($r > 100$ cms); the amplitudes of both current distributions are constant in the azimuthal direction. These distributions can be achieved in an identical manner to that proposed for the unscreened coil of 1a above.

Figures 8a and 8b show a series of equally spaced contours on the current distribution curves of the primary and screen surfaces respectively.

Screened Linear Axial Gradient Magnetic Field Coil

For the purpose of this example a cylindrical coil structure of 70 cms diameter restricted to a length of 120 cms is assumed for the primary, and a diameter of 90 cms for the screen.

Least squares optimization over the ROI resulted in the current distributions shown in Figures 9a and 9b for the primary and screen, respectively. The corresponding equipotential contours, or equally coil windings, are respectively shown in Figures 10a and 10b. These current distributions provide a magnetic field which varies linearly with distance along the axis in the ROI, Figure 11a, and zero external to the screen ($r > 45$ cms); the amplitudes of both current distributions are constant in the azimuthal direction. For comparison purposes Figure 11b shows the distorted linear magnetic gradient field provided by a prior art Maxwell coil arrangement of equal radius to the primary coil.

Screened Linear Transverse Gradient Magnetic Field Coil

In this example, a cylindrical coil structure of 70 cms diameter restricted to a length of 120 cms is assumed for the primary, and a diameter of 90 cms for the screen.

Least squares optimization over the ROI results in the current distributions shown in Figures 12a and 12b for the primary and screen, respectively. These current distributions provide a magnetic field in the axial direction which varies linearly with distance along the radius in the ROI, Figure 11a, and is zero external to the screen ($r>45$ cms); the amplitudes of both current distributions vary cosinusoidally ($m=1$) in the azimuthal direction. Figure 13 shows four quadrants where the surface has been unrolled to display the contour on the flat axial and circumferential plane. Figure 14 shows the unrolled view of a quadrant of the associated screen coil.

Generalized Solution

The foregoing has concentrated on the application of solutions over a specific ROI. For each ROI the problem must be reworked. As with the designs based on spherical harmonics, solutions exist which are scale independent, provided some loss of optimization is tolerated. A general solution can be achieved for surface current distributions by determining the current distribution required to provide the desired field at the surface of the conductor. The resultant design can subsequently be scaled. Such a solution is akin to the effect of introducing super conducting surfaces, or highly conductive ones, into a magnetic field, or rapidly changing ones respectively, for the design of unscreened gradient coils as discussed in UK Patent 8714435.

This general 'super-conducting' solution can be obtained with an iterative procedure starting from a current distribution which is simply proportional to the magnetic field required, as in the case of solutions for a flat surface, i.e. where successive approximations for the current distribution J are given by:

$$J_{n+1} = J_n (B - B_n) / \mu \qquad (10)$$

where B is the desired field at the surface and B_n is the field from the current distribution J_n.

An alternative general solution in the case of cylindrical coils is to base the length of the primary on the spacings used in line element solutions. In the case of uniform and linear axial gradients this would mean having lengths equal to the Helmholtz separation (a/2) and twice the Maxwell separation ($a\sqrt{3}/2$) respectively.

The least squares optimization for screened coil design has the advantage that it can be utilized for surfaces of arbitrary shape. The problem becomes more complicated with the loss of symmetry and the need to specify shapes of increasing degrees of arbitrariness in three dimensions. The general, iterative 'super-conducting' process described above also shares these advantages and disadvantages when applied to structures of increasingly arbitrary surface configuration.

Though no effort have been made to minimize the inductance, this system produces coils for which the inductance differs only slightly from the minimal. In addition, this minimization can be incorporated into coils designed according to the present invention, but only at some cost of field optimization.

It is anticipated that this invention can be implemented in all aspects of electromagnet design where external fields are undesirable. For example, it may have applications in particle accelerators and for the protection of electronic circuitry, such as computers, proximate to large magnetic fields. Also, it is expected that the combination of the precise profiling of magnetic fields and the suppression of extraneous fields will become increasingly important with the advancements of superconductor magnet technology, and particularly with the development of higher temperature superconducting materials.

<u>Flat Coils</u>

If the plane of the current distribution, J, is defined to be normal to the x axis then Fourier Transformation of the Biot-Savart equation in the two dimensions (y, z) gives:

$$B(x, v, w) = \frac{\mu_o}{2} e^{-|x|q} J(v, w)\, g \tag{11}$$

where

$$g = \frac{x}{|x|} i + \frac{v}{|q|} j + \frac{w}{|q|} k \tag{12}$$

and

$$q = (v^2 + w^2)^{1/2} \tag{13}$$

and v and w are the Fourier kernal dimensions corresponding to y and z, respectively.

The solutions for any particular restricted geometric shape, rectangular, circular, elliptical etc., can again be derived by simply considering the permissible harmonic modes.

<u>What is claimed:</u>

1. A method of forming an electromagnetic coil construction having a magnetic field of a given type comprising:
forming an open primary electromagnetic coil of restricted length;
forming a screening electromagnetic coil for screening said primary coil; and constructing said coils employing least squares optimization of the current amplitudes of the permissible harmonics of a hypothetical primary surface to determine the current distribution in said coils such that a substantially null magnetic field is created in one volumetric region adjacent to the screening coil and said field of said given type is created in a second volumetric region adjacent to said primary coil wherein said field of a given type exhibits substantially negligible distortion.

2. The method of claim 1 including forming the coils on a cylindrical former, the method including determining the field of a current hoop of a given dimension and of unit current amplitude which varies azimuthally as cos (m0) in the second volumetric region from the azimuthal current of the hoop by determining the axial component of the two dimensional Fourier transform in the azimuthal and axial directions of the magnetic field created by the current hoop at a given radius in a kernal space corresponding to the axial dimension of the current hoop at a radius of the current hoop, deriving the remaining current components, convolving the resultant current with a purely axial distribution function, and optimizing the convolved current by least squares minimization of said current amplitude over the second volumetric region and then forming the coils based on said optimizing.

3. The method of claim 1 including forming the coils on two coaxial cylindrical formers and determining the field B of a current hoop of a given dimension of unit current amplitude which varies azimuthally as cos (m0) in the second volumetric region from azimuthal current J by determining the axial component B_h of the two dimensional Fourier transform in the azimuthal and axial directions of the magnetic field of radius r in a kernal space K corresponding to the axial dimension z of the hoop at radius <u>a</u> of the hoop according to the relation:

$$B_h(r, m, k) = \begin{cases} \mu\, K\, a\, I'_m(Ka)\, K_m(Kr) & r > a \\ \mu\, K\, a\, I_m(Ka)\, K'_m(Kr) & r < a \end{cases}$$

where I_m and K_m are modified Bessel functions and I'_m and K'_m are their derivatives,

deriving the remaining current components, convolving the resultant current with a purely axial distribution function, and optimizing the convolved current by least squares minimization over the one volumetric region.

4. The method of claim 2 wherein said convolving includes expressing the current distribution as the sum of permissible harmonic modes n on the surface of the current hoop and Fourier transforming the resultant current distribution in the axial direction.

5. The method of claim 4 wherein said Fourier transforming includes producing a current distribution according to the relation:

$B(r, m, k) = J_0(a, k) \cdot B_h(r, m, k)$

where B_h is the axial component of the Fourier transform in the azimuthal and axial directions of the magnetic field at radius r, k is the kernal space dimension corresponding to the axial dimension z, a is the radius of the hoop and the current distribution on the surface of an open cylinder of length L having harmonic nodes n is:

$J_0(a, z) = \pi L \sum_n C_n H(z) \cos(2\pi nz/L + \S)$

and $J_0(a, k)$ is the Fourier transform of J_0 having coefficients C_n where C_n is the current amplitude of the n^{th} harmonic and wherein the parameters of the coil is derived by solving for least squares minimization of the initial few terms C_n of the latter Fourier transform over the second volumetric region in actual space.

6. The method of claim 1 wherein said constructing step comprises performing successive approximations of the current distribution J of said coils according to the relation:

$J_{n+1} = J_n + (B - B_n)/\mu$

where B is the desired field at the surface of the coil, B_n is the field from the

current distribution J_n and μ is the permeability of the space of the second volumetric region.

7. The method of claim 1 including forming the coils on cylindrical formers.

8. The method of claim 1 including forming the coils as flat coils.

9. An electromagnetic coil construction for creating a magnetic field of a given type comprising:
an open primary electromagnetic coil of restricted length; and
a screening electromagnetic coil;
said coils being constructed employing least squares optimization of the current amplitudes of the permissible harmonics of a hypothetical primary surface to determine the current distributions in said coils such that a substantially null magnetic field is created in one volumetric region adjacent to the screening coil and said field of said given type is created in a second volumetric region adjacent to said primary coil wherein said field of a given type exhibits a substantially negligible distortion.

10. The construction of claim 9 wherein said coils are constructed on a cylindrical former, the coils being formed by determining the field of a current hoop of a given dimension having a unit current amplitude which varies azimuthally as cos (m0) in the second volumetric region from the azimuthal current of the current hoop by determining the axial component of the two dimensional Fourier transform in the azimuthal and axial directions of the magnetic field created by the current hoop at a given radius in a kernal space corresponding to the axial dimension of the hoop at a radius of the hoop, deriving the remaining current components, convolving the resultant current with a purely axial distribution function, and optimizing the convolved current by least squares minimization of said current ampllitudes over the second volumetric region and then forming the coils based on said optimizing.

11. The method of claim 1 wherein said constructing step comprises utilizing cylindrical formers the primary lengths of which are related to the spacings provided by spherical harmonic analysis, examples of which are a length of a/2 for uniform magnetic fields and a length of $a\sqrt{3}/2$ for the production of linear axial magnetic fields.

12. The method of claim 1 in wherein said constructing step comprises a region of interest in said second volumetric region the surface of which is immediately proximate to the primary coil and furthest from the screen coil.

13. A coil construction comprising:
first and second current carrying coils respectively having a cylindrical surface the inner of which is a primary coil of pre-assigned length and the outer of which is a screen coil of length 1 such that 1 encompasses the significant portion of g of the total current of the coil, said coils having structures approximating the current distributions therein, the current distributions which the coil structure approximates are such that they provide simultaneously a null magnetic field external to the screen surface and a magnetic field optimized on at least square basis within a given region of interest within the primary coil to provide a field of a given form.

FIG. 1
PRIOR ART

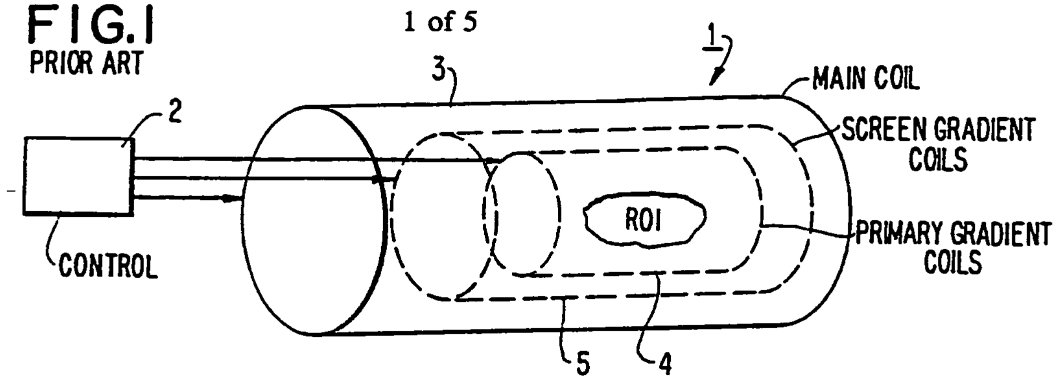


FIG. 2

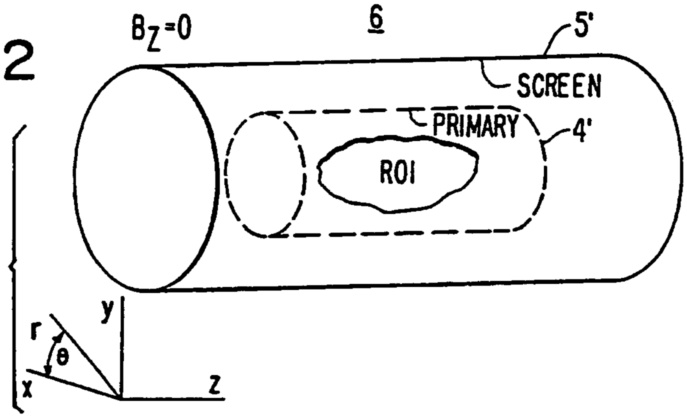


FIG. 3

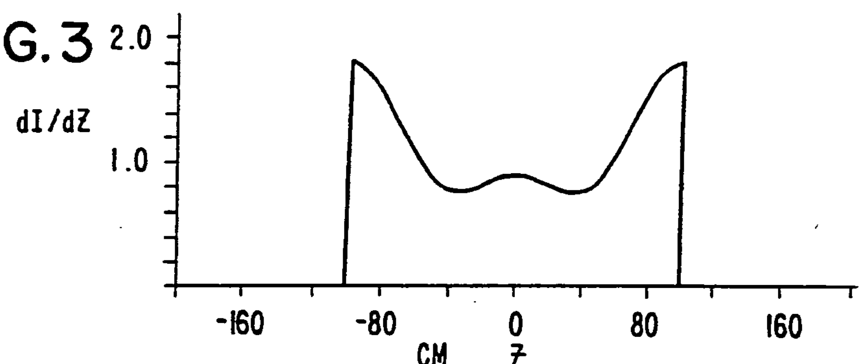


FIG. 4

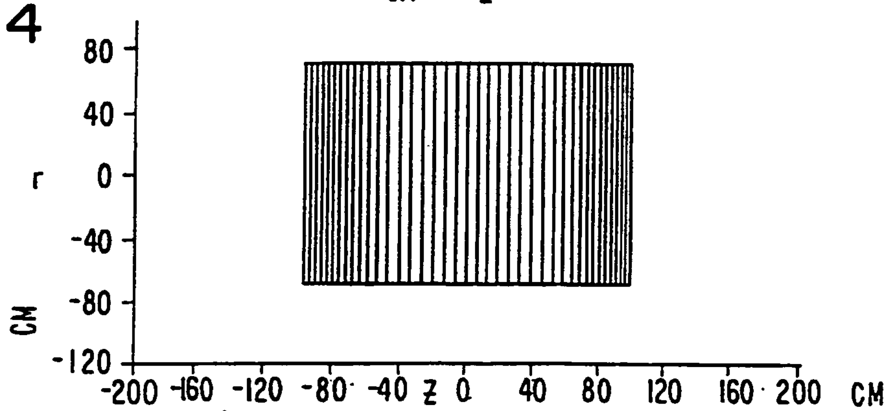


FIG.5

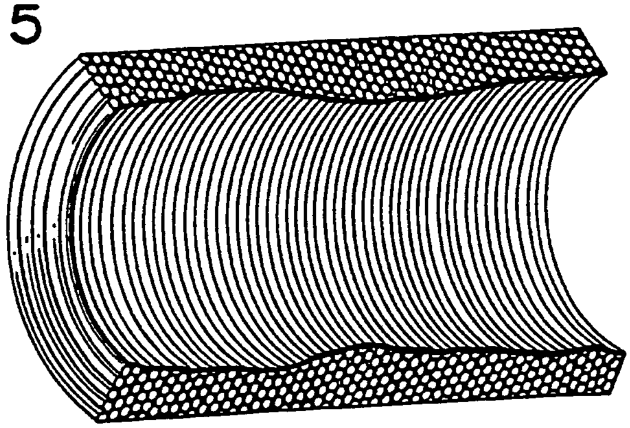


FIG.7a

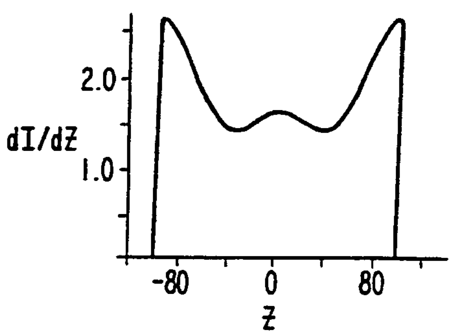


FIG.7b

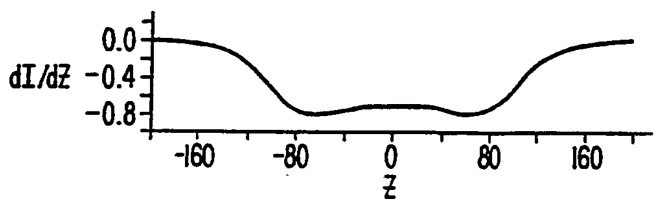


FIG.8a

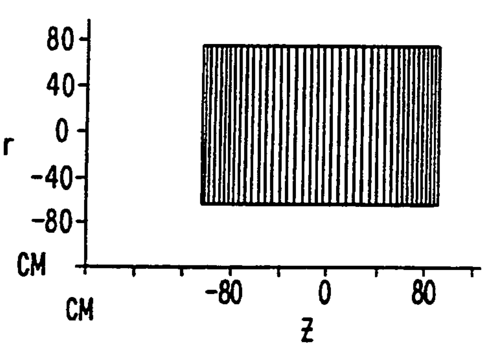
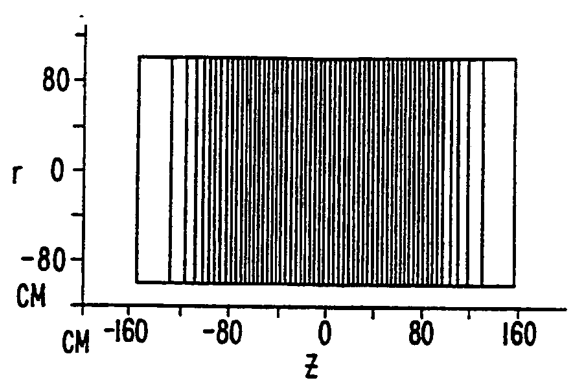


FIG.8b



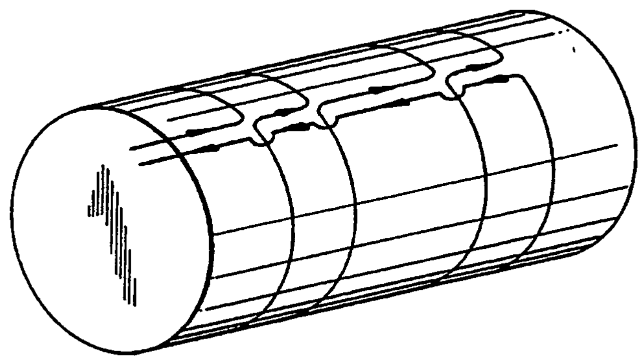


FIG. 6a

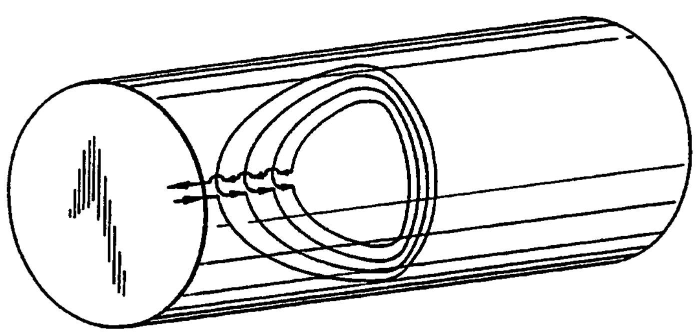


FIG. 6b

FIG.9a

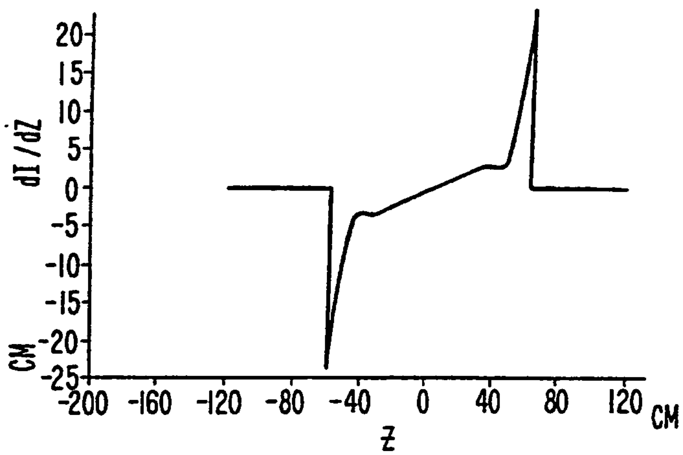


FIG.9b

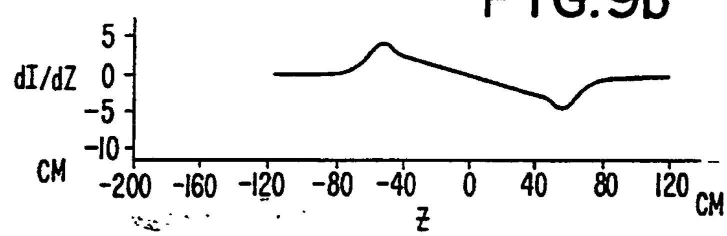


FIG.10a

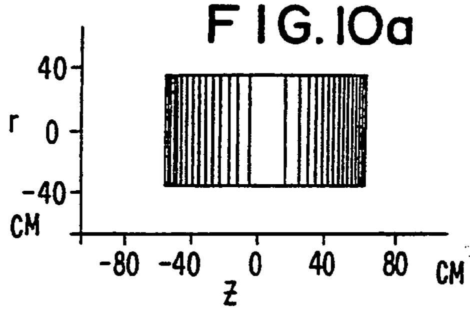


FIG.10b

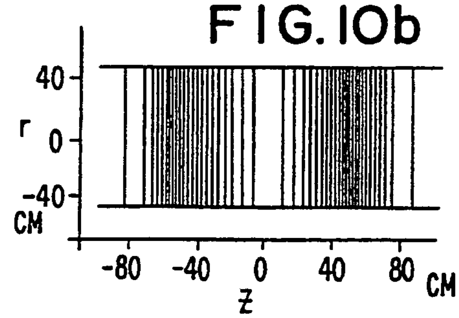


FIG.11a

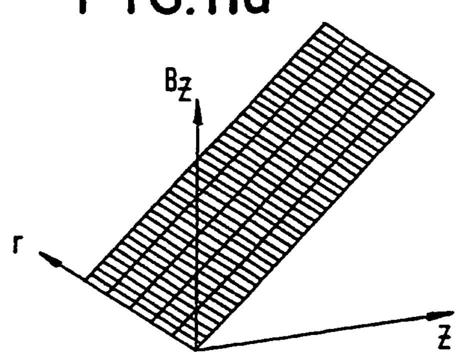


FIG.11b

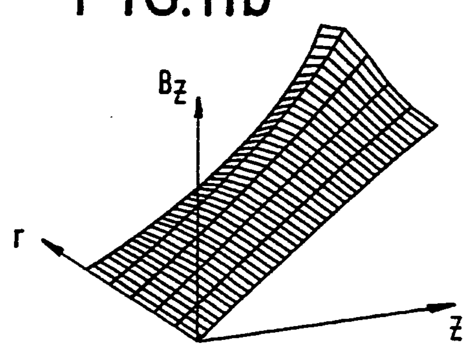


FIG. 12a

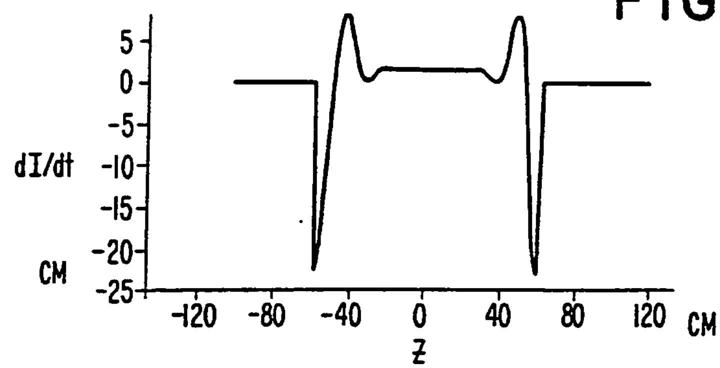


FIG. 12b

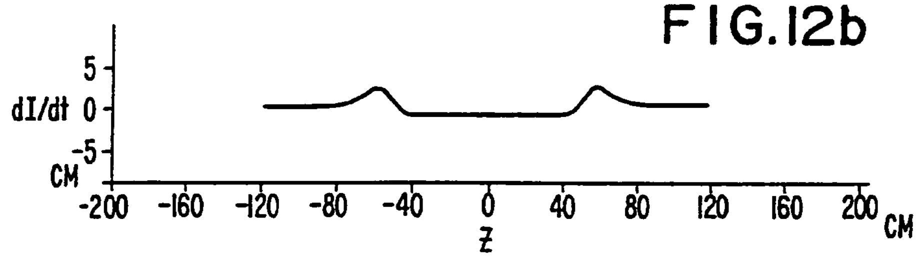


FIG. 13

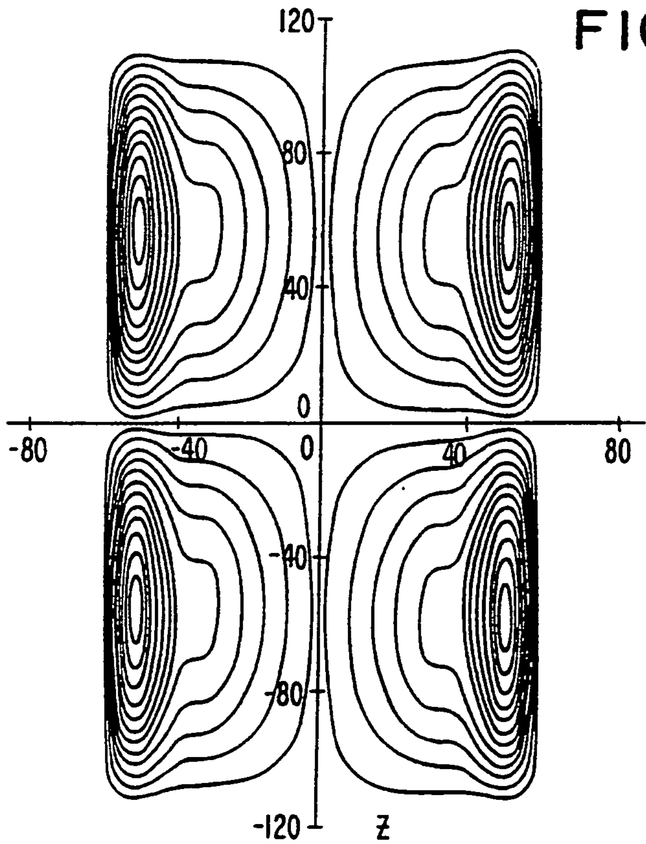
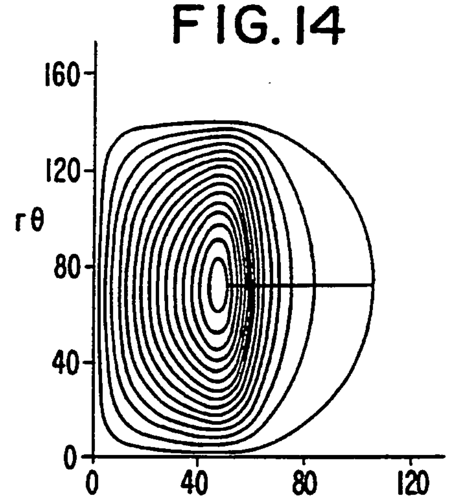


FIG. 14



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US92/07354

A. CLASSIFICATION OF SUBJECT MATTER
IPC(5) :H01F 7/00
US CL :335/216
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 335/199, 216 301, 304; 324/218, 300, 307, 309

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

NONE

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	US, A, 4,853,663 (VERMILYEA) 01 August 1989, see entire document.	1-13
Y	US, A, 4,978,920 (MANSFIELD et al.) 18 December 1990, see entire document.	1-13
Y	US, A, 4,974,338 (ROEMER et al.) 27 December 1988, see entire document.	1-13

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:

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"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
05 OCTOBER 1992	02 DEC 1992

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